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(54) Title: VERTICALLY AND LATERALLY CONFINED 3D OPTICAL COUPLER

(57) Abstract: An on-chip silicon-based optical coupler used to guide light from an optical fiber to a waveguide. The incoming wave is confined vertically by stacks of graded index materials. In the lateral direction, a linear taper formed by etched holes or trenches confines the wave.

VERTICALLY AND LATERALLY CONFINED 3D OPTICAL COUPLER

PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/289,627 filed May 8, 2001.

BACKGROUND OF THE INVENTION

The invention relates to the field of optical couplers, and in particular to optical couplers that couple light between optical fiber and on-chip optical waveguides.

Integrated Optical Circuits (IOCs) have been under development for a number of years. The designers of these circuits seek to integrate several optical functions on a single semiconductor chip. IOCs generally include waveguides formed from several layers of material. For example, in a two-dimensional planar waveguide, a core layer is sandwiched between two layers of clad material.

There is a need to couple light from optical fibers to these on-chip waveguides and vice versa. However, there are a number of other factors that complicate such coupling. First, IOCs are typically high index-contrast systems so as to provide stronger light confinement in smaller dimensions, while optical fibers are low index-contrast systems. That is, there is a much larger refractive index difference between a waveguide's core and cladding than between a fiber's core and cladding. Second, there is a mode diameter mismatch between fibers and waveguides. For example, a fiber may have a core diameter of 8-10m, while a single-mode waveguide core may have a width of 0.6-2m and thickness of 0.6-2.0m. Lastly, there is a mode shape mismatch. Fiber typically maintains a circular mode field, while waveguides typically maintain an elliptical mode field. Thus, as shown in figure 1, if a fiber is directly butt-coupled to a waveguide, high power losses occur. In figure 1 the fiber is directly butt-coupled to the waveguide at z=4 μm.

Some common fiber-to-chip coupling schemes have arisen in an attempt to overcome such losses. To confine light in the vertical dimension, prior schemes have used GRIN lenses on the fiber-side or high silica graded index stacks on-chip. For example, Shiraishi et al in "*Spot size reducer for standard SMF utilizing a graded-index fiber tip,*" 11[th] International Conference Optical Communications- Vol. 1, No. 97- pp 50-3, has demonstrated that a tip with a square-law index profile can be used as a spot size reducer. In this paper, the authors reported a method to reduce the single-mode fiber spot size to 5 m that uses a quarter-pitch length of a graded-index fiber

(GIF).

On the chip side, a planar GRIN lens on silica has been fabricated as described by Beltrami et al in *"Planar graded-index (GRIN) PECVD lens,"* Electronics Letters- 14th March 96- Vol. 32; No. 6, pp 549-50. In this paper, the author varies n around 1.44 by adjusting the F doping (CF_4 flow in oxide PECVD). The periodic refocusing effect of the parabolic profile is demonstrated. Use of doping to achieve the profile, however, prevents an index of refraction higher than 1.46.

To confine light in the lateral dimension, a laterally tapered waveguide has been used to couple from a photonic device to a single-mode fiber. However, a direct tapered structure has not been used for coupling from a single-mode fiber to a waveguide since there is no practical way to vertically taper an on-chip structure to provide vertical confinement. A lateral taper alone still results in high-coupling loss. One way to solve the problem is a tapered rib waveguide used in conjunction with a much bigger mesa waveguide underneath, as shown by Smith et al in *"Reduced coupling loss using a tapered-rib adiabatic-following fiber coupler"* IEEE Photonics Technology Letters Vol. 8, No. 8, August 96- pp 1052-4. Light is injected in the mesa, coupling up due to higher n and the tapered ridge. This device still has a size on the millimeter order.

Whatever the precise merits, features and advantages of the above cited references, none of them achieve or fulfills the purposes of the invention.

SUMMARY OF THE INVENTION

One aspect of the invention provides an optical coupler used to guide light from an optical fiber to a waveguide. The optical coupler comprises a vertical stack of varying refractive index layers formed on a cladding layer. The layers gradually decrease in refractive index from a top layer to a center layer and then increase from the center layer to a bottom layer formed on the cladding layer. The vertical stack has at least one pair of horizontally spaced trenches or periodic holes that increase in dimensions from a first end of the stack to a second end of the stack so as to form a tapered shape in the stack.

Another aspect of the invention provides a method of producing an optical coupler used to guide light from an optical fiber to a waveguide. A cladding layer is provided. A vertical stack of varying refractive index layers is formed by depositing layers of varying refractive index material on the cladding layer. The layers gradually decrease in refractive index from a top layer to a center layer and then increase from the center layer to a bottom layer. At least one pair of horizontally spaced trenches or periodic holes are etched in the vertical stack that increase in dimensions from a first end of the stack to a second end of the stack so as to form a tapered shape in the stack.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates the high power losses that occur if a fiber is directly butt-coupled to a waveguide;

Figure 2a illustrates a birds-eye view of a three-dimensional fiber-to-waveguide coupler according to the principles of the present invention;

Figure 2b a side view of a three-dimensional fiber-to-waveguide coupler according to the principles of the present invention;

Figure 2c a top view of a three-dimensional fiber-to-waveguide coupler according to the principles of the present invention using etched trenches;

Figure 2d a top view of a three-dimensional fiber-to-waveguide coupler according to the principles of the present invention using etched periodic holes;

Figures 3a and 3b illustrates the general design parameters for simulations of the vertical confinement for a coupler according to the principles of the present invention;

Figures 3c, 3d and 3e illustrate beam propagation simulations for differing parameters of the coupler of figure 3a with a Gaussian input wave;

Figures 3f illustrates FDTD (finite difference time domain) simulations for differing parameters of the coupler of figure 3a with a Gaussian input wave;

Figure 4a illustrates the general design parameters for simulations of the lateral confinement for a coupler according to the principles of the present invention; and Figures 4b, 4c, and 4d illustrate FDTD simulations for the coupler of figure 4a with different lengths.

DETAILED DESCRIPTION OF THE INVENTION

The invention provides for an on-chip optical coupler used to guide light from an optical fiber to a waveguide. The incoming wave is confined vertically by stacks of graded index materials. In the lateral direction, a linear taper formed by etched holes or trenches confines the wave.

The present invention allows for a coupler to be fabricated that reduces the spot size of incoming infrared light (1550 nm) from a diameter of 8-10μm to less than 1μm when coupling such light from a single mode fiber to a single mode silicon nitride waveguide. The present invention also allows such a coupler to be on the order of one hundred microns in size.

Figure 2a illustrates a birds-eye view of a three-dimensional fiber-to-waveguide coupler 200 according to the principles of the present invention. As shown, coupler 200 is a waveguide formed on-chip that couples light from an optical fiber 204 to a waveguide 206 made of, for example, silicon nitride (SiN) or silicon oxynitride (SiON).

Waveguide 200 is formed by depositing layers of a core material having varying refractive indexes on an underlying cladding 208, which is formed on top of a substrate 210. Preferably, waveguide 206 is integrated into center layer 212, thus eliminating the out-coupling loss to waveguide 206. Referring to figure 2b, which illustrates a side view of coupler 200, the varying index layers gradually decrease in refractive index from the top of coupler 200 to the center and then increase from the center of coupler 200 towards the lower cladding. For example, a top layer 216 is (1.5x)% doped SiO_2 (doped with, for example, N). Moving towards the center, each layer is increasingly doped to increase the index until center layer 212, which is (10x)% doped SiO_2. Moving from center layer 212, each layer is decreasingly doped until bottom layer 214 on top of undercladding layer 208.

This layer is x% doped SiO_2. This vertical stack of varying refractive index layers compresses the optical mode in the vertical direction towards the middle of the structure.

Waveguide200 also has horizontally etched trenches or periodic holes 202 that increase in dimensions from the fiber-end of waveguide 200 to the waveguide-end so as to form a tapered shape in the stack. Figure 2c illustrates a top view showing etched trenches, while figure 2d illustrates a top view showing etched periodic holes. The etched trenches or holes provide a graded effective index contrast with the highest contrast at the waveguide-end. This guides light towards the middle of the structure, laterally.

When periodic holes are used as shown in figure 2d, the periodicity (a_h, a_v) of the holes is less than half the wavelength of light in the medium to allow guided modes. Also, the dimensions (l_l, w_l) of the holes or trenches are on the order of the wavelength of the light in the medium to avoid scattering. While the holes/trenches can be air filled, they are preferably back-filled with a solid material to provide greater mechanical stability for the structure.

Figure 3a illustrates the general design parameters for simulations of the vertical confinement for a coupler 300 according to the principles of the present invention. Coupler 300 is generally designed to couple between a silica optical fiber 302 (n=1.46; core diameter 8-10μm) and a single-mode waveguide 304 (n=2.0-2.5; width = 0.8-2.0μm; thickness = 0.8-2.0μm). Coupler 300 has a refractive index increasing parabolically from 1.46 to n_{max}, where n_{max} is the refractive index of center layer 306. That is, $n(y)=n_{max}(1-y^2/2h^2)$ where y is the vertical distance from the center; and h correlates the stack thickness and its maximum, minimum indices of refraction. The normalized n(y) profile is illustrated in figure 3b. Coupler 300 is 8μm high and has a

length less than 10μm.

Figures 3c, 3d and 3e illustrate beam propagation simulations for coupler 300 with a gaussian input wave at a waist of 8μm. The following table summarizes the parameters and coupling efficiency of the simulations shown in these figures:

	n_{max}	Δn	Center waveguide thickness (w_2) [μm]	# of layers (top or bottom)	Coupling Efficiency	Length of coupler at max efficiency [μm]
Figure 3c	2.0	0.54	1.5	5	0.85	8
Figure 3d	2.0	0.54	1.5	8	0.87	8
Figure 3e	2.5	1.04	0.8	10	0.83	6

As can be seen from the simulations, the number of graded index layers does not significantly affect the coupling efficiency. Therefore, there is a high tolerance in processing this vertical structure. Figure 3f illustrates a finite difference time domain (FDTD) simulation for coupler 300 with n_{max} = 2.0, 8 layers, and a length of 8μm.

Figure 4a illustrates the general design parameters for simulations of the lateral confinement for a coupler 400 according to the principles of the present invention. Coupler 400 is generally designed to couple between a silica optical fiber 402 (n=1.46; core diameter 8-10μm) and a single-mode waveguide 404 (n=2.0-2.5; width = .6-2.0μm; thickness = 0.6-2.0μm). Coupler 400 has tapered trenches 402 in it for lateral confinement. Trenches 402 increase in dimension from a fiber–end to a waveguide-end. The width between the trenches at the fiber-end is 8μm and 2μm at the waveguide-end. Coupler 400 is 12μm wide. Trenches 402 are air-filled.

Figures 4b, 4c, and 4d illustrate FDTD simulations for coupler 400 with different lengths. Figure 4b illustrates FDTD results for a coupler length of 10μm. As can be seen, for a coupler length this short, multimode develops within the taper, causing a low coupling to the fundamental mode. However, as shown in figure 4c, when the length is increased to 25μm, there is only a single mode at the taper end and approximately 0.85 power is coupled to even modes. Similarly, as illustrated in figure 4c, there is only a single mode at the fiber-end for an inverse propagation from waveguide to fiber when the length is 25μm.

One of skill in the art will appreciate that the coupler can be any type of waveguide, such as a ridge, strip or channel waveguide. Also, the index grading in the

vertical direction can take on a number of different functions. For example, the grading function can be a parabolic, exponential, sine, cosine, or sinh function. Furthermore, materials for the vertical stack other than SiO_2 can be used, such as SiON or SiN.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, .may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

CLAIMS

1. An optical coupler used to guide light from an optical fiber to a waveguide comprising:

a cladding layer;

a vertical stack of varying refractive index layers, wherein the layers gradually decrease in refractive index from a top layer to a center layer and then increase from the center layer to a bottom layer formed on the cladding layer;

at least one pair of horizontally spaced trenches or periodic holes in the vertical stack that increase in dimensions from a first end of the stack to a second end of the stack so as to form a tapered shape in the stack.

2. The coupler as per claim 1, wherein the at least one pair of trenches or holes are back-filled with a material that has a higher refractive index than air.

3. The coupler as per claim 1, wherein the waveguide is integrated with the center layer.

4. The coupler as per claim 1, wherein the at least one layer of the stack is made of SiO_2.

5. The coupler as per claim 1, wherein the at least one layer of the stack is made of SiON.

6. The coupler as per claim 1, wherein the at least one layer of the stack is made of SiN.

7. The coupler as per claim 1, wherein the waveguide is made of any one of: SiN or SiON.

8. The coupler as per claim 1, wherein the layers decrease and increase according to a grading function that is any one of: a parabolic, exponential, sine, cosine, or sinh function.

9. A method of producing an optical coupler used to guide light from an optical fiber to a waveguide, the method comprising:

providing a cladding layer;

forming a vertical stack of varying refractive index layers by depositing layers of varying refractive index material on the cladding layer, wherein the layers gradually decrease in refractive index from a top layer to a center layer and then increase from the

center layer to a bottom layer;

etching at least one pair of horizontally spaced trenches or periodic holes in the vertical stack that increase in dimensions from a first end of the stack to a second end of the stack so as to form a tapered shape in the stack.

10. The coupler as per claim 9, wherein the at least one pair of trenches or holes are back-filled with a material that has a higher refractive index than air.

11. The coupler as per claim 9, wherein the waveguide is integrated with the center layer.

12. The coupler as per claim 9, wherein the at least one layer of the stack is made of SiO_2.

13. The coupler as per claim 9, wherein the at least one layer of the stack is made of SiON.

14. The coupler as per claim 9, wherein the at least one layer of the stack is made of any one of: SiN or SiON.

15. The coupler as per claim 9, wherein the waveguide is made of SiN.

16. The coupler as per claim 8, wherein the layers decrease and increase according to a grading function that is any one of: a parabolic, exponential, sine, cosine, or sinh function.

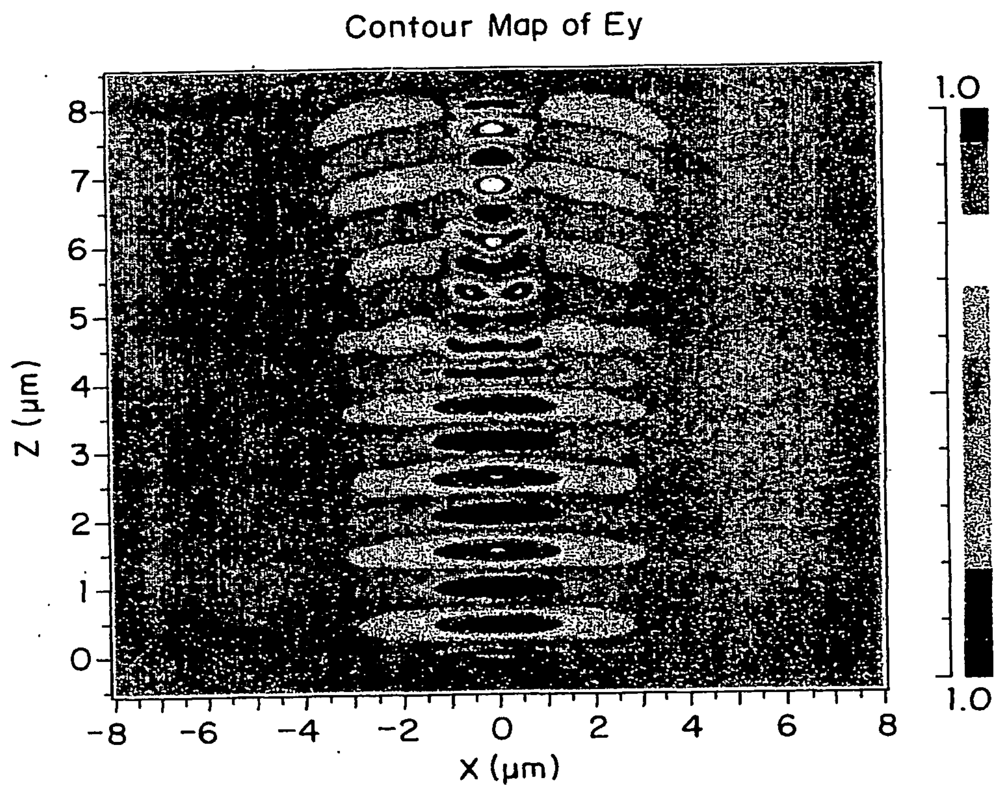

FIG. 1

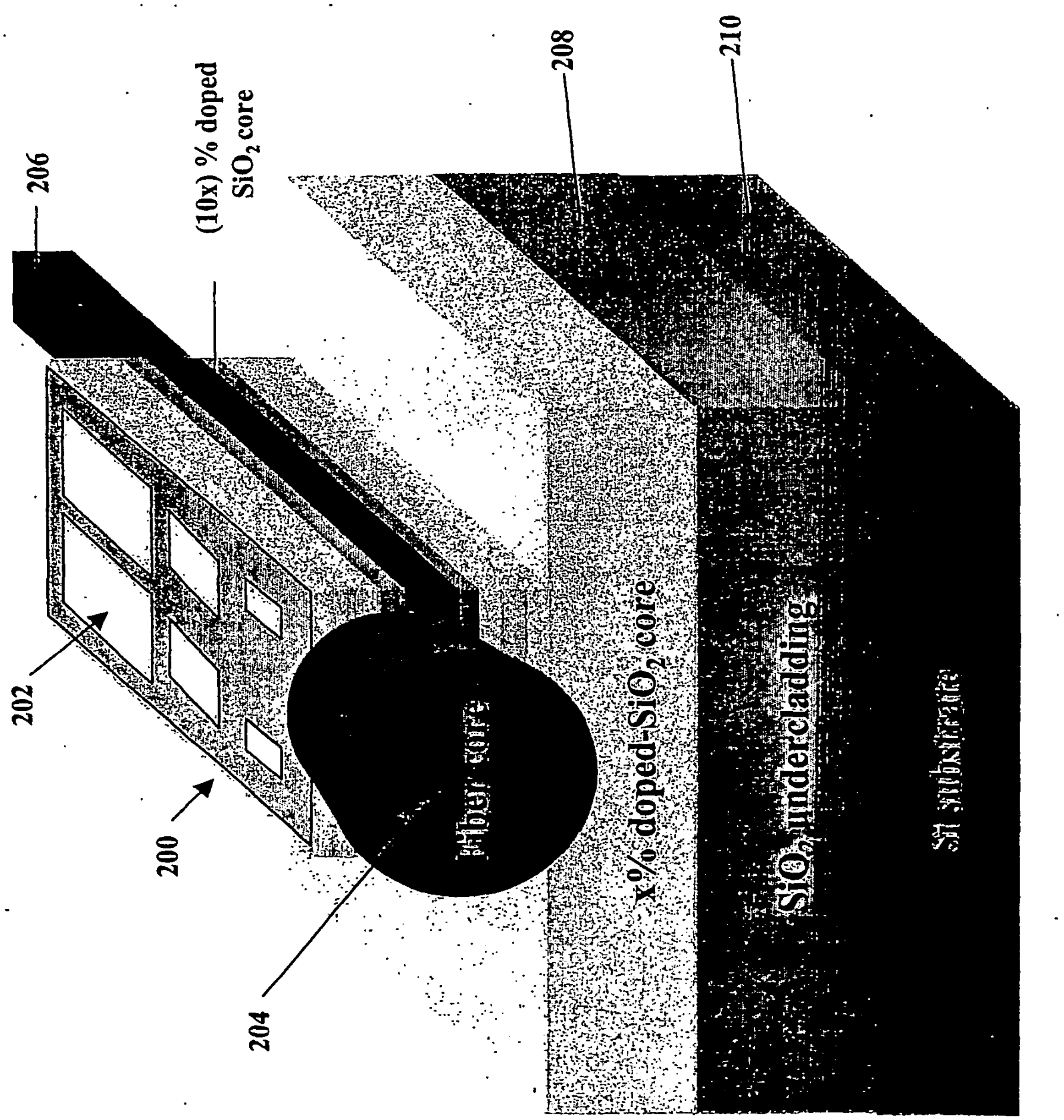
206
(10x) % doped
SiO_2 core
208
210
202
200
204
fiber core
x% doped-SiO_2 core
SiO_2 undercladding

FIG. 2A

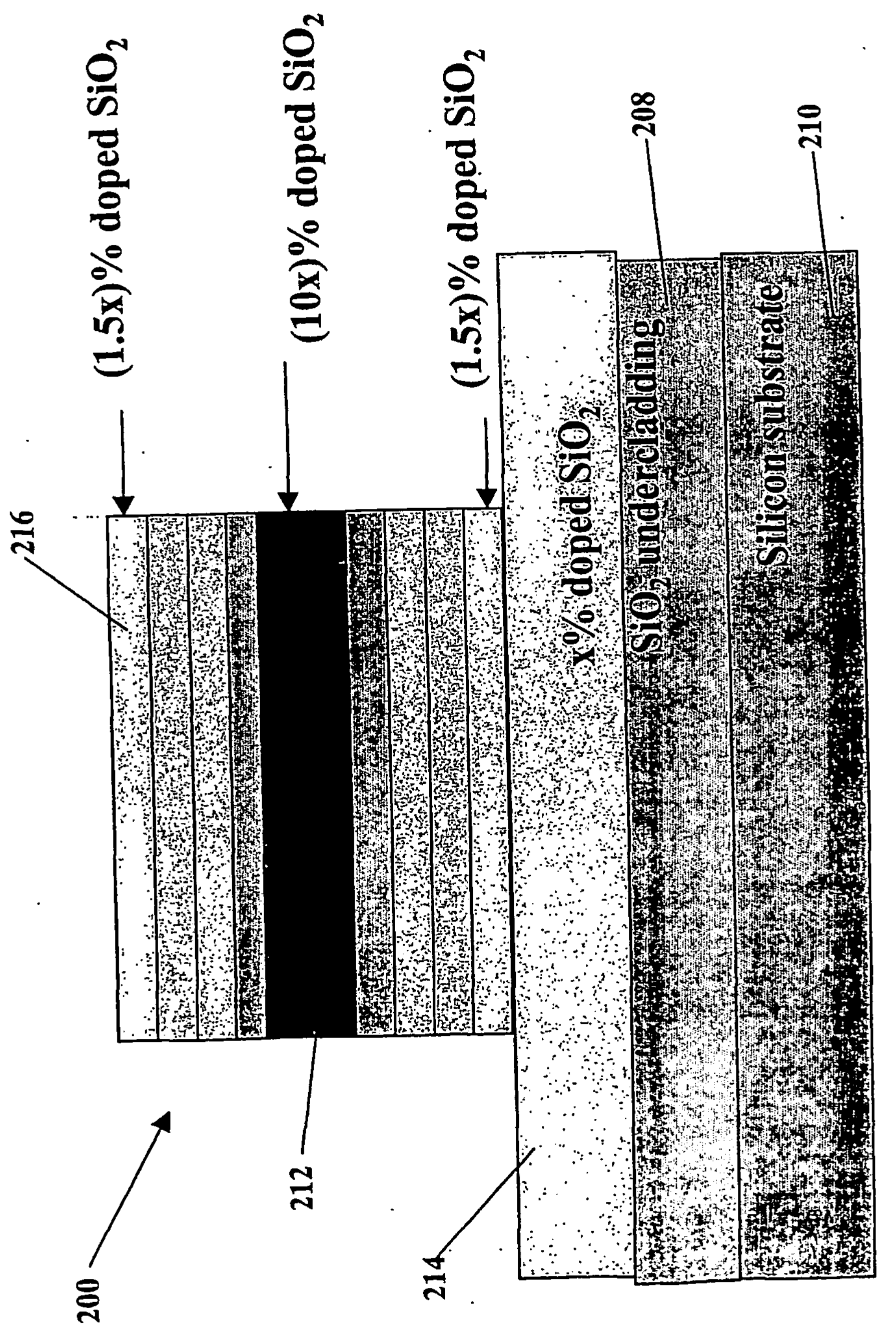
(1.5x)% doped SiO_2
(10x)% doped SiO_2
(1.5x)% doped SiO_2
x% doped SiO_2
SiO_2 undercladding
Silicon substrate
208
210
216
212
214
200

FIG. 2B

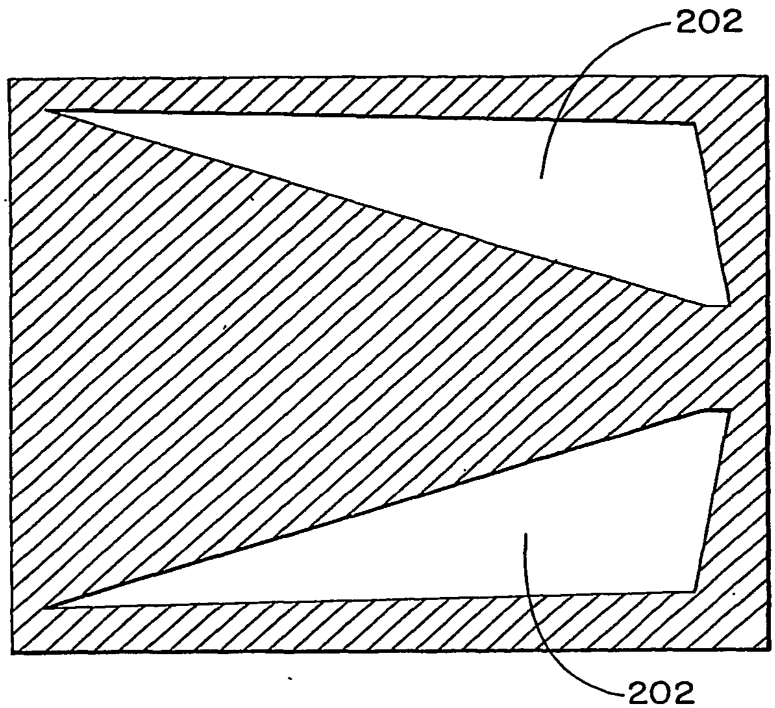

FIG. 2C

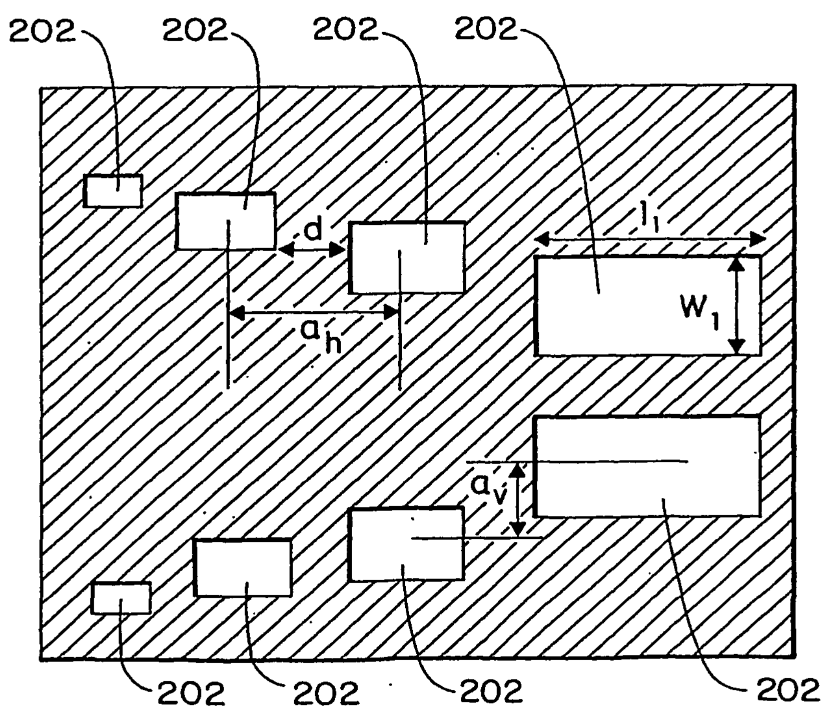

FIG. 2D

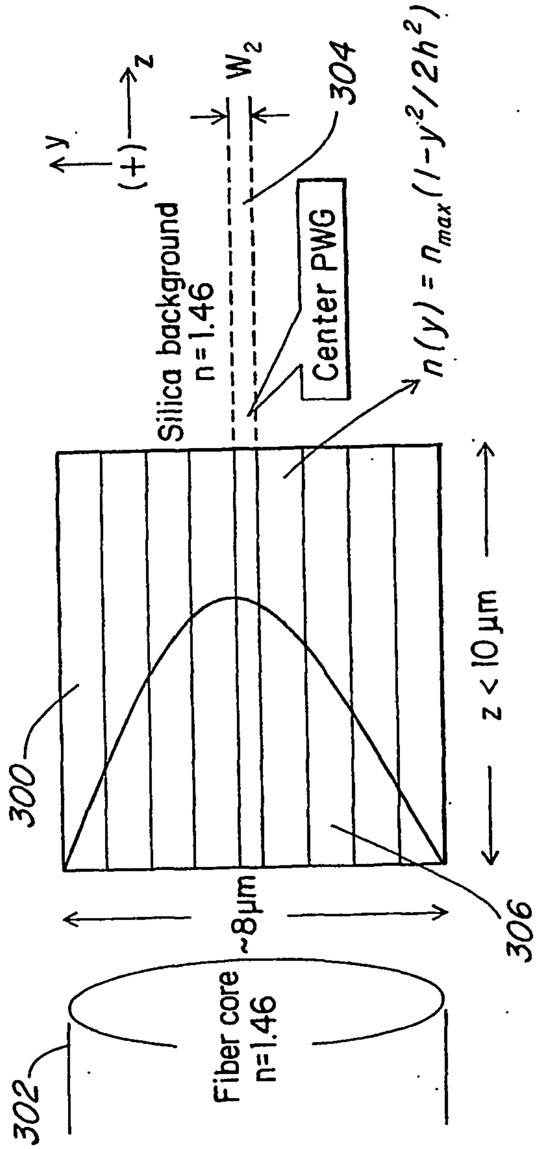
Silica background
n=1.46
y
(+)
z
W_2
304
Center PWG
$n(y) = n_{max}(1-y^2/2h^2)$
300
z < 10 µm
~8µm
306
Fiber core
n=1.46
302

FIG. 3A

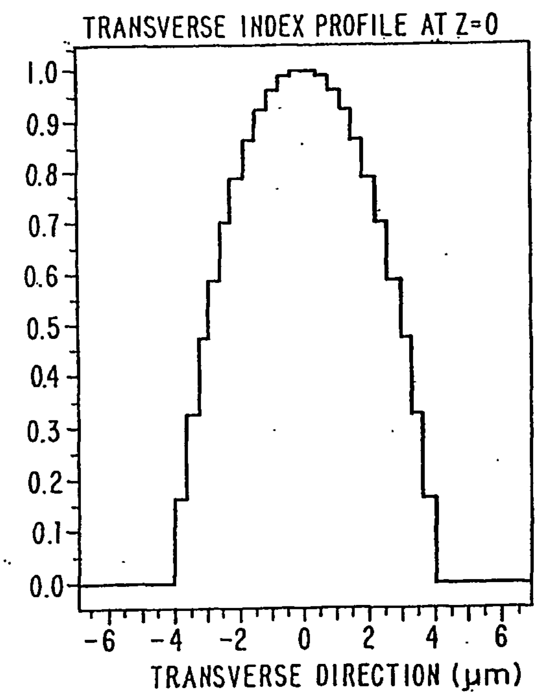
TRANSVERSE INDEX PROFILE AT Z=0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-6 -4 -2 0 2 4 6
TRANSVERSE DIRECTION (µm)

FIG. 3B

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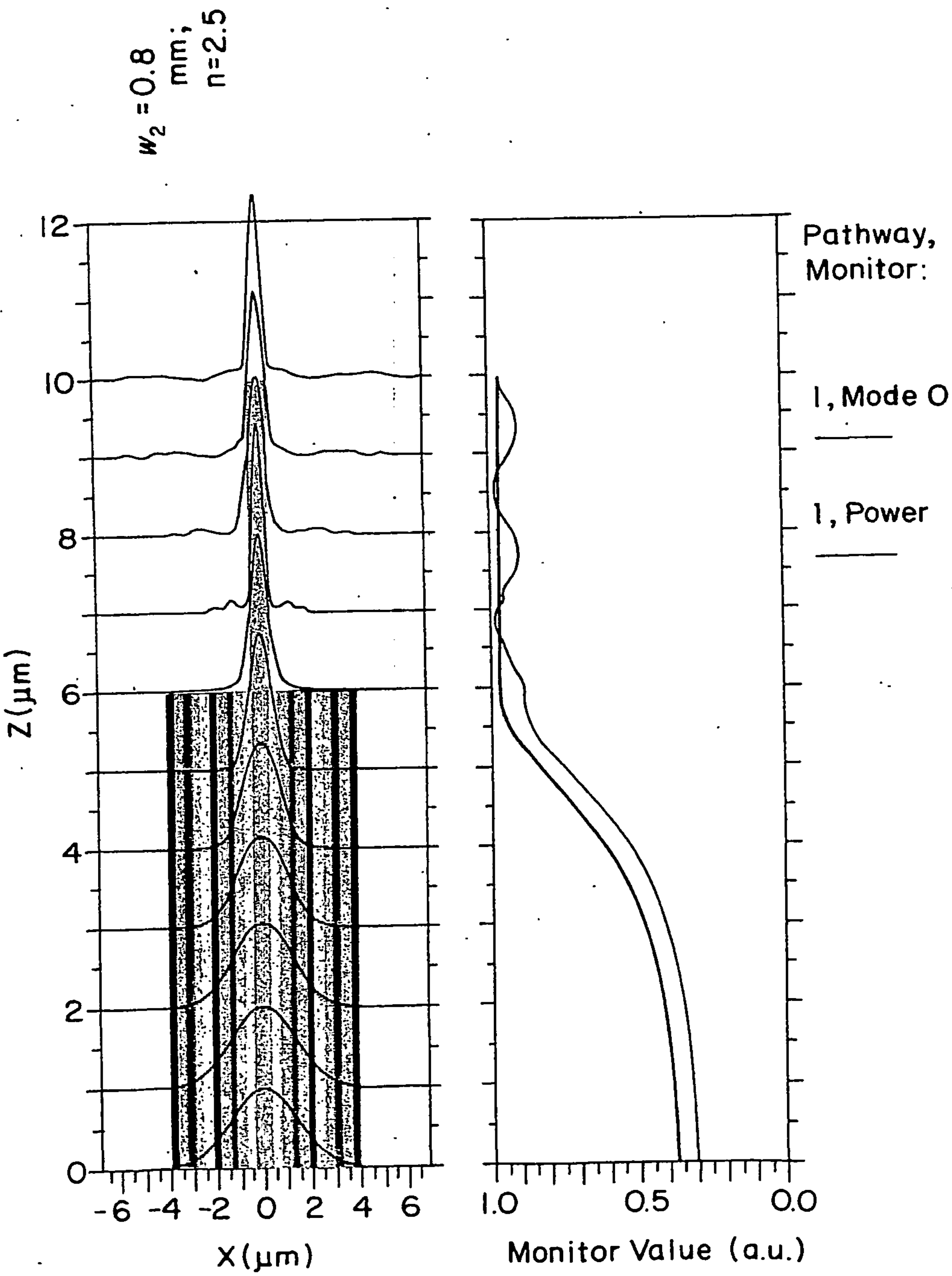
Vertical confinement- Result for n_{max}=2.5



Simulation shows coupling efficiency of 0.83 at L=6mm

FIG. 3C

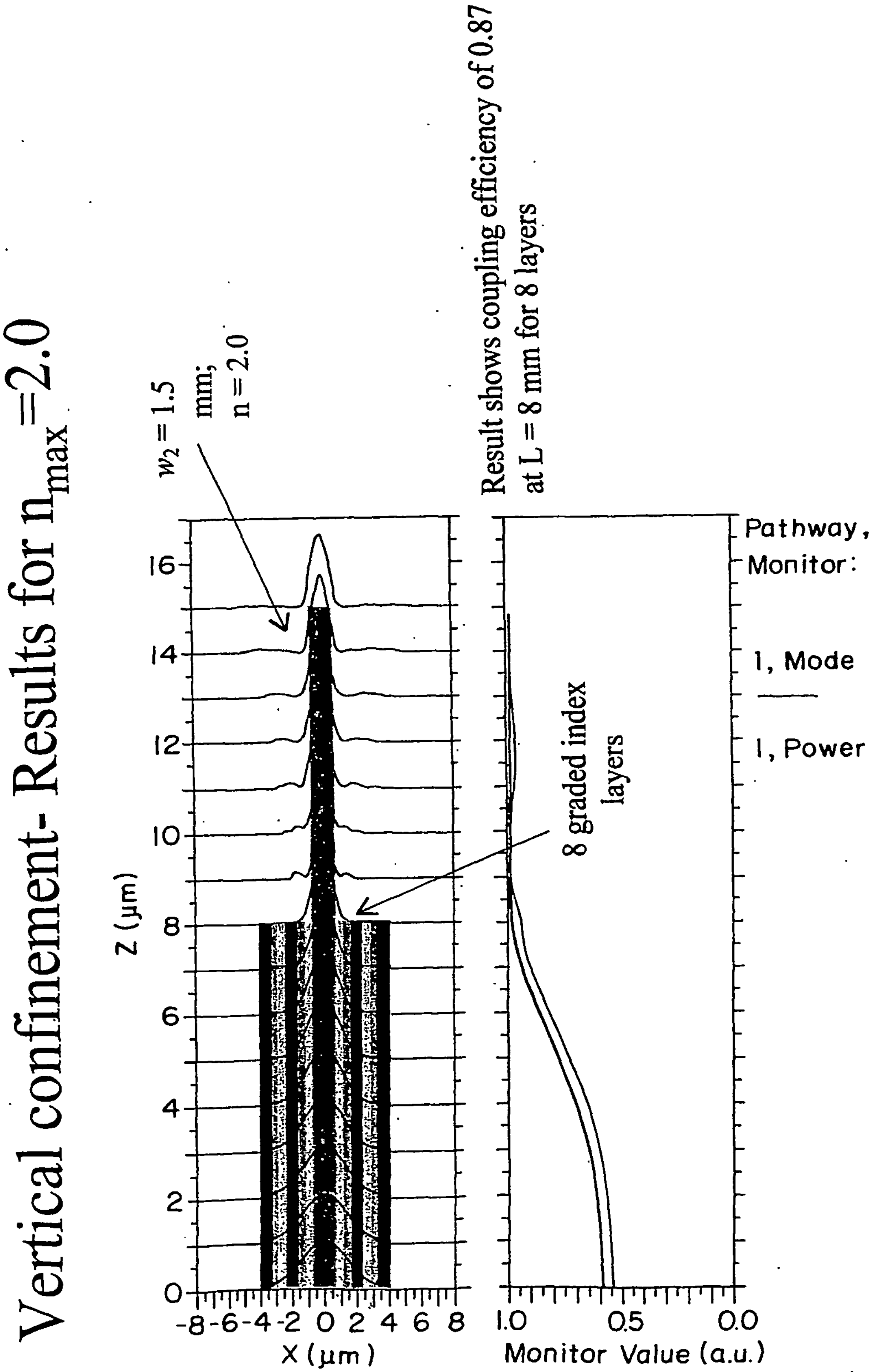

Vertical confinement- Results for n_{max}=2.0
$w_2 = 1.5$ mm; n = 2.0
Result shows coupling efficiency of 0.87 at L = 8 mm for 8 layers
8 graded index layers
Z (μm)
X (μm)
-8 -6 -4 -2 0 2 4 6 8
0 2 4 6 8 10 12 14 16
Pathway, Monitor:
1, Mode
1, Power
1.0 0.5 0.0
Monitor Value (a.u.)

FIG. 3D

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Vertical confinement- Results for $n_{max}=2.0$

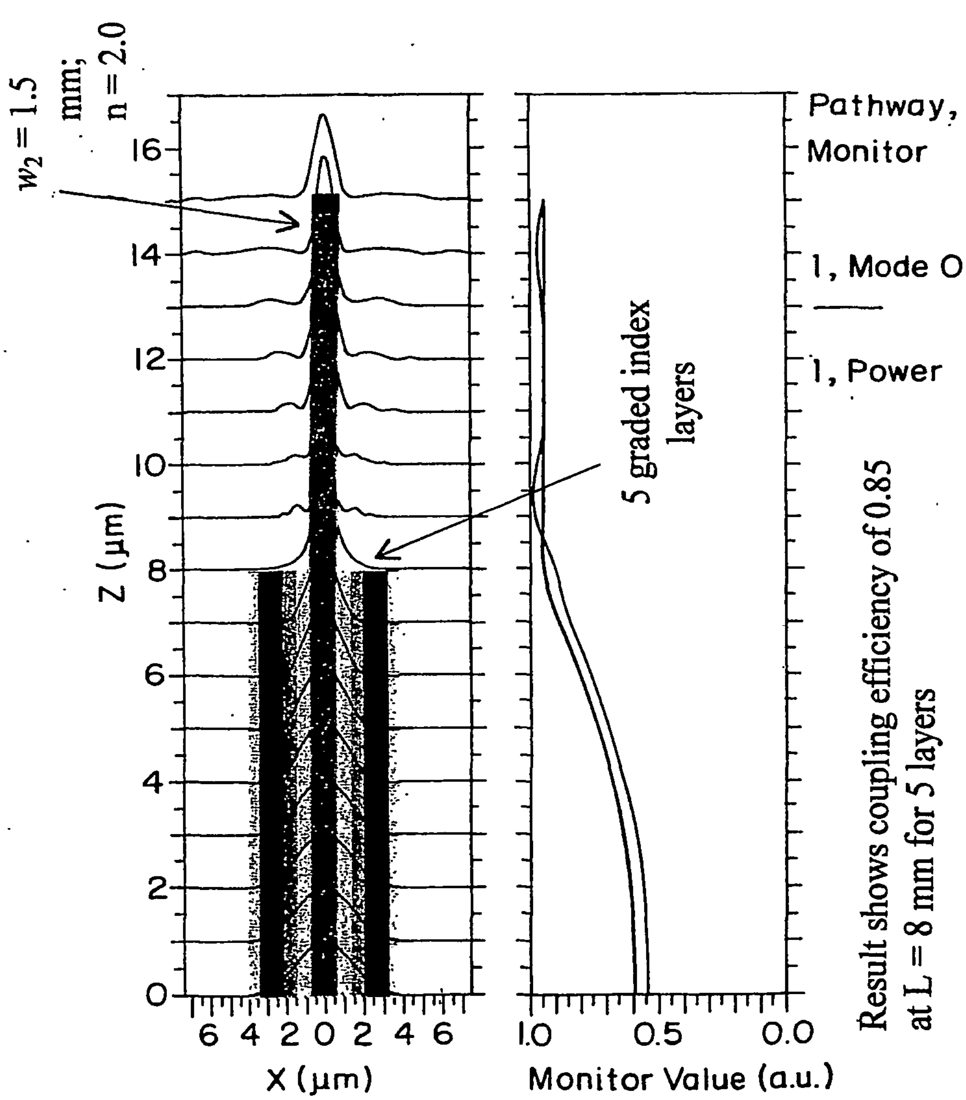

FIG. 3E

SUBSTITUTE SHEET (RULE 26)

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Vertical confinement- FDTD result for

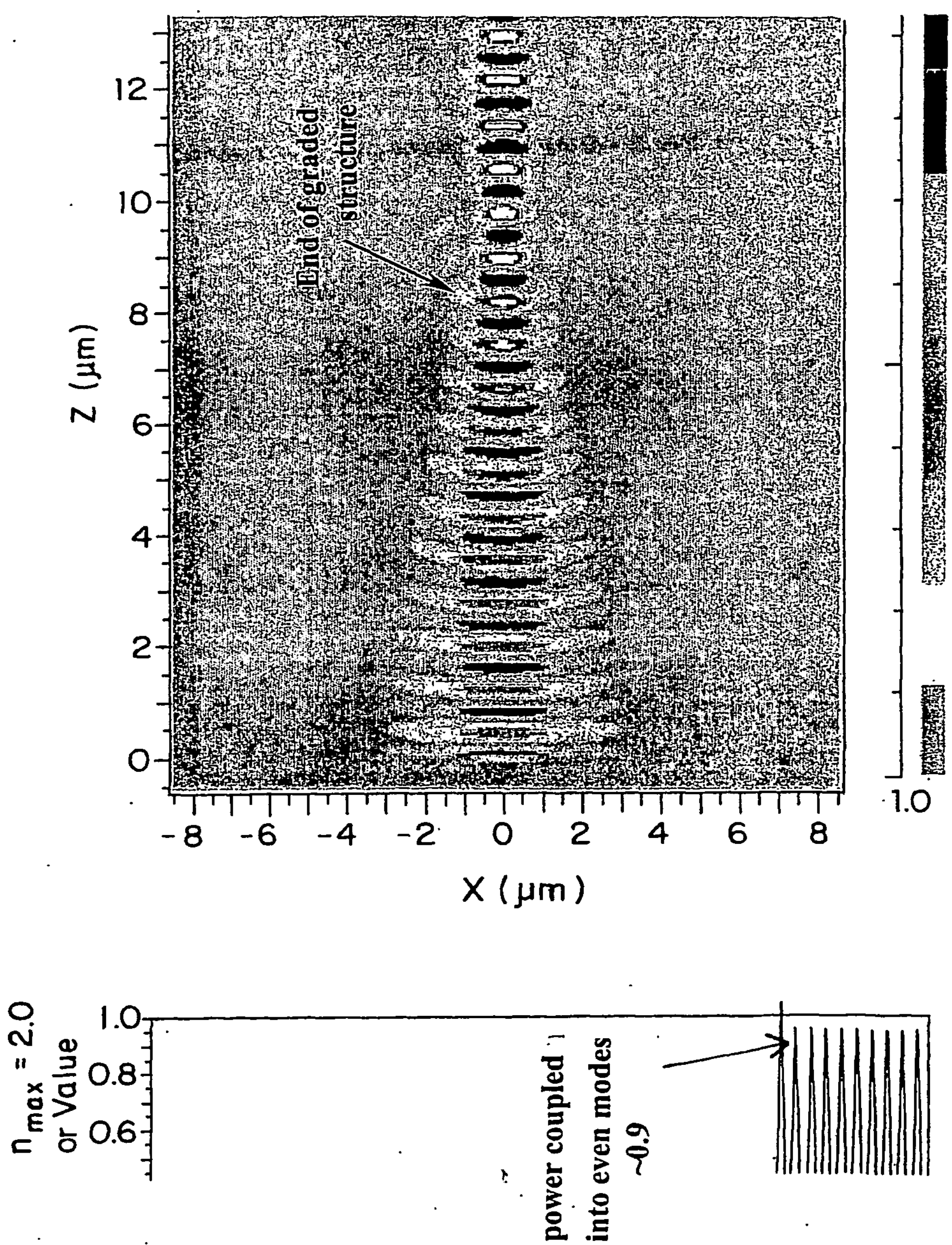

FIG. 3F

SUBSTITUTE SHEET (RULE 26)

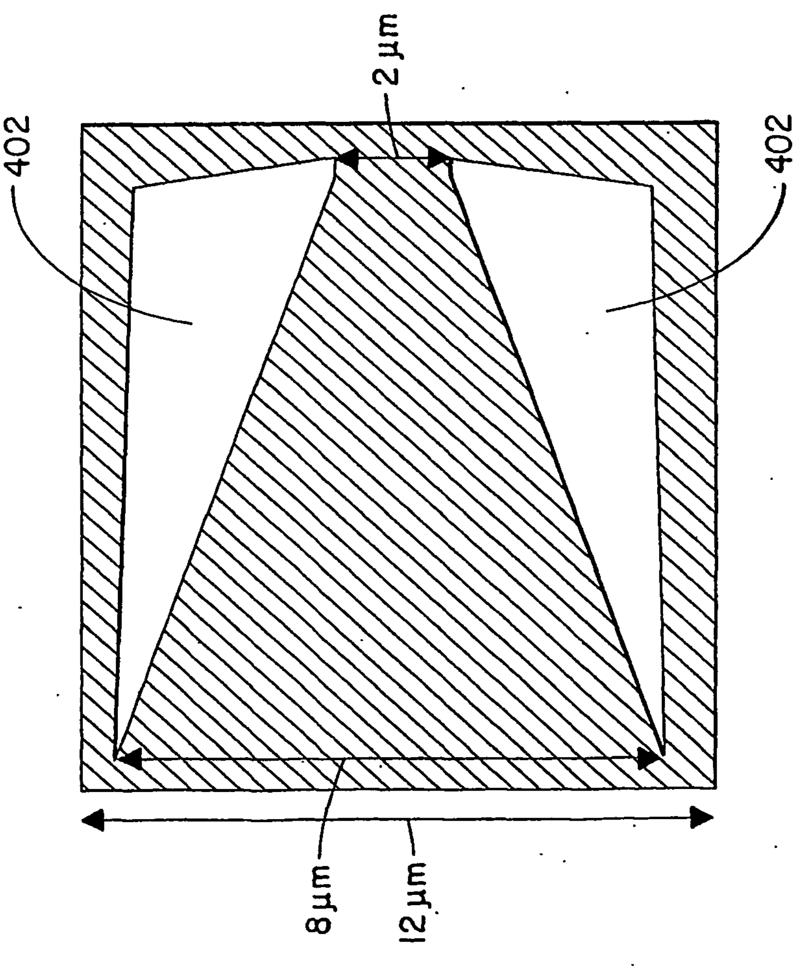

FIG. 4A

Lateral confinement- L=10 μm

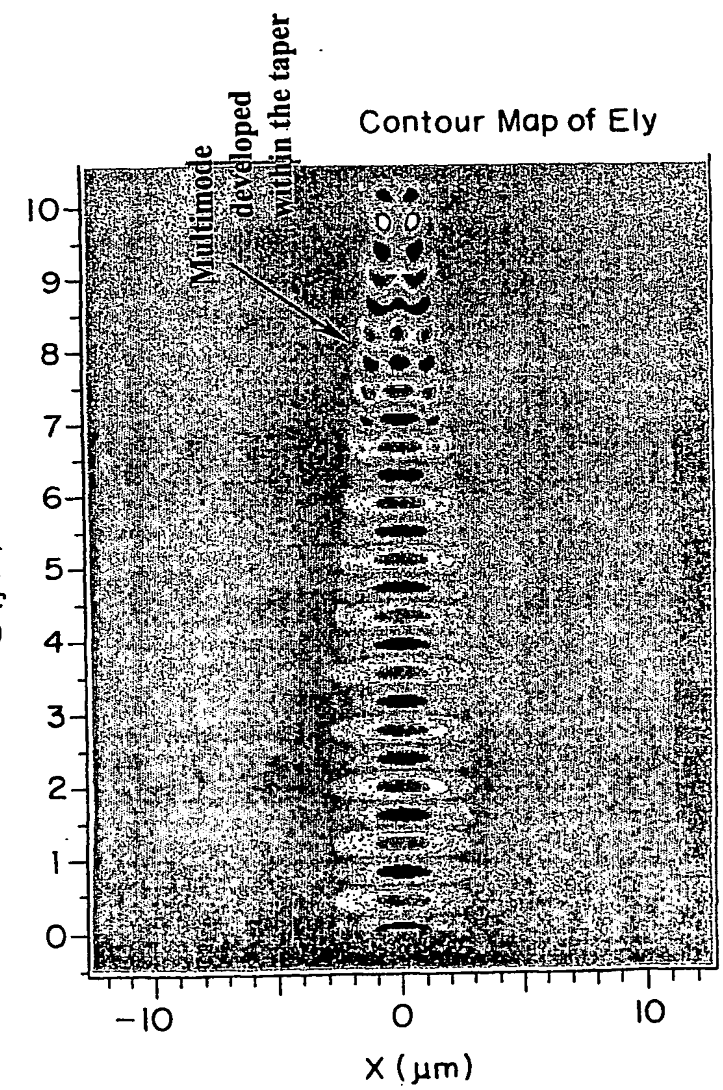

FIG. 4B

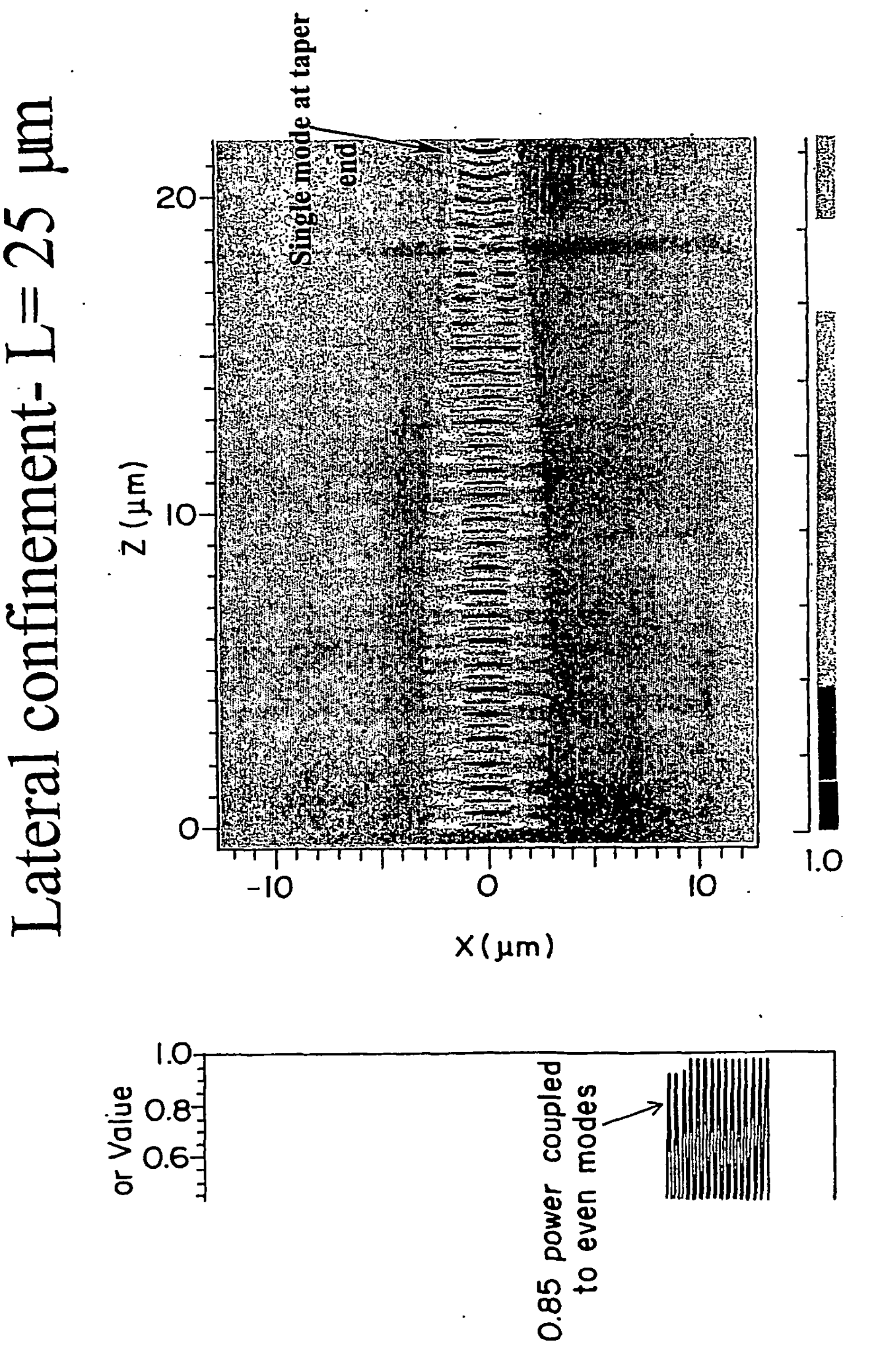
Lateral confinement- L= 25 µm
Single mode at taper end
Z (µm)
X (µm)
0
10
20
-10
0
10
1.0
or Value
1.0
0.8
0.6
0.85 power coupled to even modes

FIG. 4C

Lateral confinement- L= 25 μm- Inverse

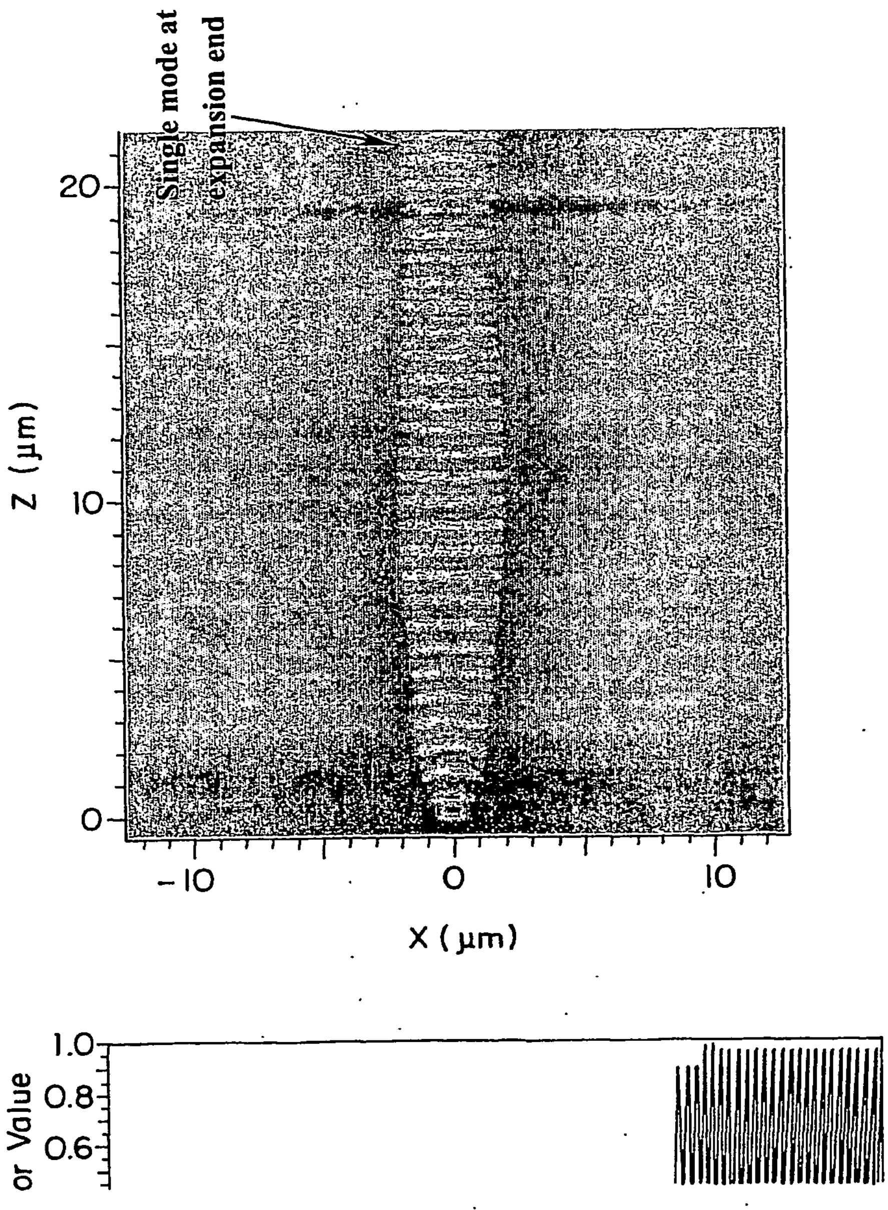

FIG. 4D

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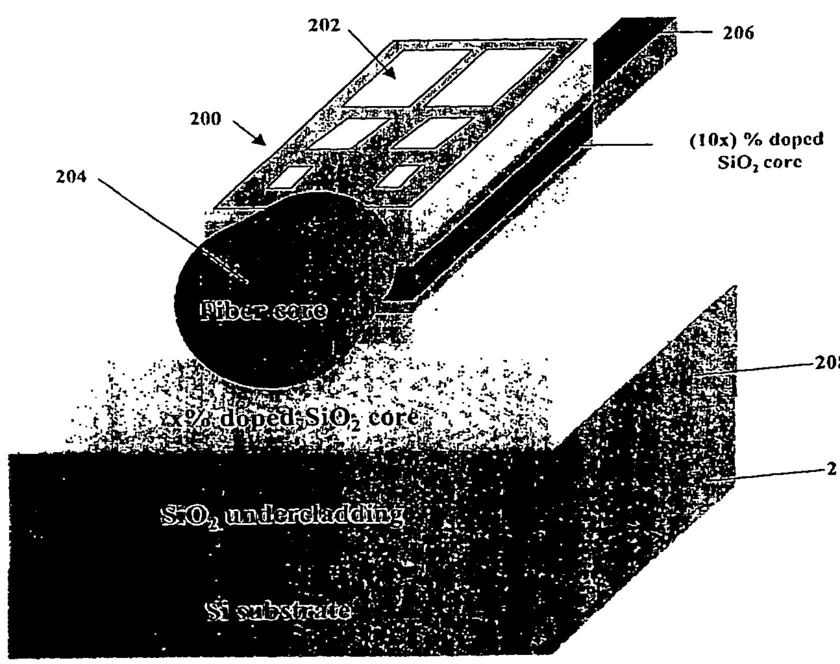

(57) Abstract: An on-chip silicon-based optical coupler (200) used to guide light from an optical fiber (204) to a waveguide (206). The incoming wave is confined vertically by stacks of graded index materials. In the lateral direction, a linear taper formed by etched holes (202) or trenches confines the wave.

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GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report*

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/14386

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/30 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 731 367 A (AT & T CORP) 11 September 1996 (1996-09-11) column 2, line 55 -column 3, line 3 column 4, line 51 - line 58 column 6, line 4 - line 6 column 9, line 14 -column 10, line 42 figure 8 ---	1-16
Y	US 4 737 015 A (ISHIDA KOJI ET AL) 12 April 1988 (1988-04-12) column 1, line 45 -column 2, line 12 column 4, line 24 - line 54; figure 3 --- -/--	1-16

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 November 2002	15/11/2002
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Ciarrocca, M

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INTERNATIONAL SEARCH REPORT

Int ial Application No
PCT/US 02/14386

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WEISSMAN Z ET AL: "MODES OF PERIODICALLY SEGMENTED WAVEGUIDES" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE. NEW YORK, US, vol. 11, no. 7, July 1993 (1993-07), pages 1831-1838, XP000828051 ISSN: 0733-8724 page 1836, right-hand column, last paragraph	9
A	US 4 999 686 A (AUTIER PHILIPPE ET AL) 12 March 1991 (1991-03-12) column 7, line 24 - line 27 column 6, line 46 - last line; figures 6,7	1,9
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A	PATENT ABSTRACTS OF JAPAN vol. 013, no. 467 (P-948), 23 October 1989 (1989-10-23) -& JP 01 183603 A (MITSUBISHI ELECTRIC CORP), 21 July 1989 (1989-07-21) abstract	1
A	US 5 175 788 A (MIURA KAZUNORI ET AL) 29 December 1992 (1992-12-29) column 2, line 3 - line 28 column 4, line 51 - line 59; figure 4 figures 7A,7B	1

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Information on patent family members

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